



Institute for Energy

ENIQ Recommended Practice 6: The Use of Modelling in Inspection Qualification

2nd Issue

ENIQ report No. 45

ENIQ

European Network for Inspection and Qualification

The mission of the JRC-IE is to provide support to Community policies related to both nuclear and non-nuclear energy in order to ensure sustainable, secure and efficient energy production, distribution and use.

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The Use of Modelling in Inspection Qualification

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Approved by the ENIQ Steering Committee

ENIQ, the European Network for Inspection and Qualification, publishes three types of documents:

Type 1 — Consensus documents

Consensus documents contain harmonised principles, methods, approaches and procedures and emphasize the degree of harmonisation between ENIQ members.

Type 2 — Position/Discussion documents

Position/discussion documents contain compilations of ideas, express opinions, review practices, draw conclusions and make recommendations for technical projects.

Type 3 — Technical reports

Technical reports contain results of investigations, compilations of data, reviews and procedures without expressing any specific opinion or evaluation on behalf of ENIQ.

This 'ENIQ Recommended Practice 6: The Use of Modelling in Inspection Qualification' (ENIQ Report No. 45) is a Type 1 document.

FOREWORD

The present work is the outcome of the activities of the ENIQ Steering Committee.

ENIQ, the European Network for Inspection and Qualification, is driven by the nuclear utilities in the European Union and Switzerland and managed by the European Commission's Joint Research Centre (JRC). It is active in the field of in-service inspection (ISI) of nuclear power plants by non-destructive testing (NDT), and works mainly in the areas of qualification of NDT systems and risk-informed in-service inspection (RI-ISI). This technical work is performed in two task groups: TG Qualification and TG Risk.

In the recent past both ENIQ task groups have been very active. In 2005, TGR published the "European Framework Document on RI-ISI", and has since been working at producing more detailed Recommended Practices (RPs) and discussion documents on several RI-ISI related issues. Amongst these are RPs on the verification and validation of structural reliability models and guidance on the use of expert panels together with discussion documents on the application of RI ISI to the inspection of the reactor pressure vessel and updating of RI-ISI programmes. TGQ, after publishing the third issue of the European Qualification Methodology Document in 2007, has recently issued a RP on personnel qualification and a document giving an overview of inspection qualification for the non-specialist.

During its 38th meeting in April 2010 TGQ decided to update the "ENIQ Recommended Practice 6: The Use of Modelling in Inspection Qualification" to account for the progress in the use of modelling in inspection qualification since 1999 when the first issue of this recommended practice was published. This exercise resulted in the writing and publishing of this document (2nd Issue, 2011).

This ENIQ type-1 document was approved for publication by the ENIQ Steering Committee.

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1 Introduction

The European Methodology Document [1] is intended to provide a general framework for development of qualifications for the inspection of specific components, to ensure that they are developed in a coherent and consistent way throughout Europe, while still allowing qualification to be tailored in detail to meet different national requirements.

In the European Methodology Document one will not find a detailed description of how the inspection of a specific component should be qualified. A Recommended Practice is a document produced by ENIQ to support qualification activities in individual countries. It is the next level of document below the Methodology Document and is applicable in general to any qualification. This general scope means that valuable advice can be given by ENIQ to promote a uniform approach to qualification throughout Europe, while leaving the detail of how qualification is done to be determined at national level according to the regulatory and technical requirements of that country. Organisations will be free to make use of Recommended Practices of national level, as they see fit.

This document is a Recommended Practice on the use of mathematical modelling in inspection qualification. Mathematical models have been developed by several organisations for various inspection situations and, where applicable, can provide valuable evidence on inspection capability for inclusion in a technical justification. Therefore authors of technical justifications may be considering the use of models, which may be available in-house, bought in from an external organisation or run by an external organisation on their behalf. This Recommended Practice provides advice on:

- The types and range of available models;
- How the models can be used to generate evidence for a technical justification;
- Important considerations and constraints in using models;
- Validation of models and
- Training in modelling

Appendix A provides a checklist on issues that might be considered by authors of technical justifications when contemplating the use of modelling.

This Recommended Practice may be relevant to any non-destructive testing method, although examples are mainly confined to ultrasonic, eddy current and radiographic inspection since most qualifications to date have involved these methods.

The ENIQ Methodology Document was developed for in-service inspections of nuclear power components. However, it is emphasised that the general principles of

the Methodology Document and its associated Recommended Practices (including this one) can also be applied to manufacturing inspections and the inspection of non-nuclear components.

The definitions used can be found in the second issue of the ENIQ Glossary [4].

ENIQ Recommended Practice 6 “The Use of Modelling in Inspection Qualification” was first issued in December 1999. It is a living document and is reviewed regularly to take account of the latest experience gained from the use of this Recommended Practice and the latest progress in modelling approaches and technology.

2 Available Types of Models and their Applications

The purpose of modelling is to generate quantitative predictions about aspects of inspection performance through the use of mathematical models of the physical phenomena on which the NDT technique under consideration is based. Normally the mathematical model is implemented as a computational model although some mathematical models may be amenable to hand calculation using simple mathematical formulae or implementation in spreadsheets. In the following the focus is on the computational models and corresponding software codes, which will be referred to as “models” and “codes”.

A wide range of models has been developed to meet the various inspection requirements. Some models aim to fully simulate the inspection process. The input data of such models correspond to the essential parameters of the inspection and their output represents the output inspection results. Other models are focused on one aspect of the inspection process, e.g. the computation of an excitation field in a structural component, the calculation of reflection coefficients, the homogenisation of a heterogeneous or composite structure and the estimation of corresponding effective parameters (attenuation, permittivity, etc.).

Concerning the implementation of these models in codes the following types of codes can be distinguished:

- NDT oriented in-house codes developed by the end user;
- commercial NDT packages; and
- general simulation packages (commercial or in-house) such as finite element codes that are applied to solve NDT-related issues.

Typical applications for these codes related to ultrasonic inspection are:

- Calculation of ultrasonic ray paths or wave fields in components of complex geometry, possibly including reflections off postulated defects;

- Predicting echo amplitudes from postulated defects as a function of probe position and orientation; and
- Predicting ray paths or wave fields in anisotropic and possibly inhomogeneous material such as an austenitic weld metal, possibly including reflections off postulated defects.

For eddy current inspection typical applications are:

- Predicting impedance variations from postulated defects with probe position and frequency, in plate, tube and other geometries; and
- Predicting electric and magnetic field distributions.

For radiographic inspection typical applications include:

- Determination of optical density variations from postulated defects;
- Calculation of build-up factors; and
- Examining the effect of changing source, exposure and set-up parameters.

3 Use of Modelling in Technical Justification

3.1 Advantages of Using Modelling

Modelling can be an attractive option for generating evidence on inspection capability for technical justifications. It has three key advantages over the alternative approach of performing experiments on test specimens: speed, cost and versatility. The speed and cost advantages are clear. Running a model is generally much quicker and more cost efficient than manufacturing and inspecting test specimens. This is especially true if realistic defects are required in the test specimens, rather than simple reflectors such as notches or flat-bottomed holes, provided the model is able to handle realistic defects. The third advantage is that of versatility. A good model should be able to handle a wide range of inspection parameters and possible defect positions, shapes, sizes and orientations. A test specimen, by contrast, can only include a limited number of defects, and it will not normally be possible to cover the full range of plausible defects of structural concern. A good model can fill the gaps in the experimental results and reduce the number of test specimens needed. Provided they remain within their regimes of validity, models can also be used to extrapolate experimental data over the full range of essential parameters and so generalise experimental data.

Despite these advantages, modelling is rarely used alone to provide evidence for a technical justification. More usually it provides one element of evidence, alongside other sources (e.g. experimental evidence, parametric studies, physical reasoning, feedback from field experience, equipment considerations) as described in other ENIQ documents [1, 2].

3.2 Ways of Using Modelling

There are many ways in which modelling can be used to provide evidence for a technical justification. This will vary from case to case, depending on such factors as the extent of relevant experimental evidence and the availability of suitable models. In general, modelling may be used to study the effect of varying essential input, procedure or equipment parameters up to the limits of tolerance or range specified [3].

Examples of how models are currently and commonly used are:

- to predict signal amplitudes from postulated defects and determine their margins of detection above the proposed threshold level and/or above noise level. In general, threshold levels are established using the responses of calibration defects (side drilled holes, flat bottomed holes, etc.);
- to quantify the influence of parameters related to the inspected component, e.g. varying geometry, surface roughness, metallurgical characteristics (grain sizes, dendrite orientations, etc.), presence of cladding, etc. or the environmental conditions (e.g. temperature) or the equipment itself;
- to determine the most difficult defects to detect from amongst those in the defect specification (the “worst case” defects);
- to interpolate between cases covered by experimental data, in order to provide a fuller assurance of capability over the ranges of variation of influential parameters (such as defect orientation, location and size or equipment settings);
- to predict inspection capability for components of similar but slightly different geometry from those for which experimental data are available; or
- to provide physical insight that can be used further in technical arguments.

Whatever the model is used for, it may in some cases be necessary to correct the predictions to overcome known limitations of the model, or to allow for effects not included in the model (e.g. defect roughness or poor surface finish).

4 Considerations and Constraints in the Use of Models

It is clearly important to use modelling with care in order to generate high-quality evidence for a technical justification. Little credence can be given to model predictions if, for example, the model is based on unsound physics or is clearly being used outside its regime of validity. The following four issues should be addressed when considering the use of a model in a technical justification:

4.1 Physical Basis and Regime of Validity

The crucial issue when using models is to evaluate the level of reliability of the predictions provided by the model. Great care must be taken with the relevance of the computations by considering the physical basis of the model and the domain of applicability of the model. This is especially true since simulation software models are powerful tools offering multiple possibilities and are based on sophisticated mathematical and numerical theories. Basic aspects such as the following need to be considered:

- Are there aspects of the inspection that are not accounted for by the model?
- Does the model account for the influence of the essential parameters under investigation?
- What are the main underlying hypotheses and approximations of the model?
- How many dimensions does the model have, i.e. is it 2D or 3D?
- Has the model already been used or validated in the context of similar applications?

A good model should be based on sound physical principles. Owing to the complexity of real inspection situations, exact analytic solutions are unlikely to be available, and approximations will inevitably have to be made in the model. Such approximations can arise either directly in the theory itself (for example, using Kirchhoff theory or the Geometrical Theory of Diffraction for ultrasonics), or in the numerical method used, e.g. discretisation in a finite difference, finite element or boundary element approach. The underlying physical principles and approximations of each model should be well-established and well documented (with appropriate references).

All models should have a clearly defined regime of validity. For example, many ultrasonic models are restricted to homogeneous isotropic media such as ferritic steel, and become invalid for anisotropic media such as austenitic welds, where the underlying equations are more complex. Another common restriction for many ultrasonic models is that defects are assumed to be smooth. Similarly, an eddy-current model may only be valid for non-ferromagnetic media (material permeability of 1), and/or for defects having no electrical contact between their faces, while a radiography model might be applicable only within a given energy range. The approximations introduced into the model to render the problem more tractable may also limit the model's regime of validity. For example, the Geometrical Theory of Diffraction, in its simplest form, is known to fail at caustics of the diffracted field. Comparison with experiment (see below) is one method of quantifying a model's regime of validity.

In most applications, model predictions should only be cited in a technical justification if the model has been run within its own regime of validity. In some cases it may be possible to relax this constraint, for example by applying correction factors, but

evidence is then required to justify such relaxation and the magnitudes of the correction factors used.

4.2 Representation of Input Parameters

The input parameters of a simulation generally consist of qualifying characteristics (type of probe, isotropy of the material, etc.), and values of the essential physical parameters (frequency of the excitation, wave speed in the component, etc.). The representation of the real inspection by a set of input parameters is based on:

- Hypotheses relating to the component under test (geometrical assumptions, material considerations, etc.) or to the equipment behaviour (e.g. piston source behaviour of ultrasonic probes) and
- Knowledge of the values of the essential parameters.

Both items may involve approximations: also uncertainties or inaccurate determination of essential parameters may have a considerable influence on the relevance of the simulated results. Thus input parameters for every simulation have to be chosen with great care.

4.3 Validation of the Model

Validation of models is typically performed by comparison of their predictions with the results of experiments. Models that have been thoroughly validated against experiments (or other established theories) and that have satisfied performance criteria are preferred, and the validation work should be referenced in the technical justification. In certain cases it may be acceptable to use models in a technical justification which have not been fully validated. Such models should only be used in a supporting role, to explain or support experimental results, or should be explicitly validated for the cases of interest as part of the technical justification itself. This topic is further discussed in Section 5.

Comparisons between simulated and experimental data should always include both the validation of the model itself (and its implementation) and the validation of the idealisation of the inspection configuration. Whenever a code is used in a technical justification at least a few comparisons between computed and measured data should be carried out, particularly when the simulation code has been validated for similar cases only and not for the case being considered. A possible discrepancy between computation and measurement does not necessarily prohibit the use of the model in the technical justification but depending on the case (and on its possible cause) it may be used to “calibrate” the model or to estimate margins of confidence. Generally when there is a lack of available validation data for the scope considered in the technical justification it is recommended to carry out a specific validation campaign. Recommendations related to such (numerical and experimental) validation are given in Section 5.

Certain aspects of modelling, which are difficult to assess experimentally, might also be verified by cross code comparisons (see Chapter 5).

4.4 Relevant Information to be reported to the Qualification Body

Generally, in a technical justification process it must be demonstrated to the qualification body that the models used have a sound physical basis, that they are used within their regimes of validity and that they have received adequate validation against experiment and/or other theories. Additional supporting evidence is necessary such as:

- The name of the code, version (the version is of particular importance when commercial codes are used), developing organization and documentation;
- Experience of the persons running the model;
- The input parameters of the model;
- Modelling results including their accuracy;
- Elements justifying the relevance of the model, i.e.
 - the physical basis of the model and its domain of validity;
 - available and confirmed data related to the validation of the model for similar cases: data from the literature or resulting from international benchmarks, experimental databases etc.
 - Experiments carried out specifically with the aim of evaluating the reliability and accuracy of the model under study.

As well as using their in-house models, the authors of a technical justification may be considering the use of other models developed by external organisations, either by buying in the models or by contracting the external organisation to run their model on the authors' behalf. In such circumstances it is very important to ensure that the model is suitable for the authors' needs. A checklist of issues to be considered when buying in or using external models is provided for guidance in Appendix A.

5 Considerations and Recommendations for the Validation of Models

As emphasized above, the availability of validation data is a key aspect for using simulation for technical justification. The validation of a code or model is mainly the comparison of the results it delivers with reference results, normally from experiments (experimental validation, see Section 5.1) or from other models (numerical validation, see Section 5.2).

5.1 Recommendations for Experimental Validation

5.1.1 Design of Experiments

The design of experiments includes the choice or specifications for mock-ups, flaws, specimens, experimental procedures, parameter set up, etc. and is determined by the objectives of the validation. The following recommendations should be followed in the design of an experiment with the purpose of model validation:

- The test should represent the situation of interest and the range of parameters (such as flaw size, angle beams, etc.) under investigation.
- Simplify the test as much as possible, in order to isolate the phenomena under consideration and to minimize interference with other factors which might complicate the interpretation of results. If, for example, the validation concerns only the influence of the defect size or orientation on its response, simple geometries and isotropic materials will be preferred to complex mock-ups.
- Choose specimens and mock-ups whose characteristics are measureable and well-known.
- Verify the underlying assumed hypotheses for the suitability of the chosen specimen (geometrical and material properties such as isotropy, homogeneity, etc.).

5.1.2 Performance of Experiments

Concerning the experiments themselves the following recommendations should be followed:

- List all influential parameters of the experiment, determine their values and make sure that these stay within specified margins throughout the experiment.
- Check the reproducibility of the results data and report their confidence intervals.
- Perform measurements in order to determine and/or confirm the underlying hypotheses and the values of those influential parameters which are not directly controlled by the experimentalist. These are in particular:
 - The material characteristics of the mock-up, such as ultrasonic velocities, size and positions of artificial defects, etc.
 - The topology of the mock-up (profilometry)
 - The characteristics of the specimens, which are not always available especially when commercial specimen are used. In particular for specimens that are used for ultrasonic inspections, additional experiments may have to be performed in order to verify that the

characteristics of the ultrasonic beam (orientation, width, etc.) correspond to the nominal values provided by the manufacturer.

5.1.3 Performance of Computations

Concerning the input and output data the following recommendations should be followed:

- Assure correspondence between the input data of the code (pertaining to the description of the test to be simulated) and the corresponding available data from the experiment. If there is incomplete correspondence, identify and report the missing information and all the performed operations to complement the data (extrapolation, approximations, signal processing, etc.)
- Check that the results of code and experiment are in good agreement. If these are not exactly identical, report the difference quantitatively. When any post-processing of computational and/or experimental results is performed, these operations should be reported.
- Perform computations in order to evaluate the inaccuracy induced by the uncertainties in the essential parameters. These could be performed for the maximum and minimum possible values of the parameter and for at least one representative case.
- List the computational input parameters (e.g. element size and mesh density for a FE model) that do not pertain to the description of the test and check the relevance of the specified values.
- When necessary, perform tests on the influence of these computational parameters for at least one representative case. Experience shows that the accuracy of the computations can depend significantly on one or several of these parameters. In such cases the recommended practice is:
 - Increase successively the level of precision of the computation until convergence of the output data is achieved within a pre-defined interval.
 - If convergence is achieved with acceptable computer resources and within acceptable computation times, the corresponding value of the computation parameter for the case of interest should be adopted for all subsequent computations.
 - If convergence is not achieved, the uncertainty of the output data should be reported as a measure of the accuracy of the simulation.
 - In all cases the values of the computer parameters should be reported.
- When necessary, evaluate the reproducibility of the computational results and report the amplitude of the “numerical noise”.
- Report “abnormal” behaviour of the code which is in conflict with engineering understanding. This is an indication of bugs or inadequate use of the code.

5.2 Recommendations for Numerical Validations

Another way to evaluate the reliability of a model or a code (Code1) may be to compare its prediction results with the results provided by another code (Code2), considered in that test as a reference. Then the following aspects have to be taken into account:

- Agreement (within a relevant interval of accuracy) of the results of the two codes for the same situation is an indication for
 - The correct implementation of the two codes.
 - The validity of the model (mathematical formulation and its implementation by numerical algorithm) under consideration, but only if the two models considered are different in this respect.
- If different results are obtained with the two codes the drawing of conclusions is more difficult. The causes for the differences in results might be:
 - The discrepancy between the two sets of results could be attributed to the approximations of the model or to a bug in the implementation of Code 1, but only if the validity of Code 2 has been definitely proven for the input configuration of interest.
 - In addition, the discrepancy may also be due to differences between the situations considered by the codes. A careful analysis of the input parameter sets of the two codes is necessary before conclusions can be drawn. Different definitions of the parameters fed into the two codes and different adopted conventions may make this analysis difficult to perform. This is especially the case when some of the results are obtained from the literature.

6 Training

Where the user of a model is not intimately familiar with its operation (for example as a result of not being involved in its development), it is important that he/she has adequate training before making use of the model for the design or justification of an inspection technique. In the context of an ENIQ Recommended Practice it is only possible to state general principles regarding appropriate training. Any organisation making use of models of NDT techniques should develop a training programme relevant to their needs.

In developing such a programme the following aspects should be considered:

- General education: The model user needs to have sufficient educational background to be able to understand the physical principles involved in the inspection method.
- Training and experience in the inspection method: The model user should have appropriate training and experience in the inspection method. While it is not necessary for the model user to be trained as a practitioner of the method, it is necessary that he/she has sufficient training in the theory of the method and experience of its application to be able to understand its limitations.
- Training in operation of the model: The model user must be familiar with the operation of the model. Depending on the quality of documentation of the model and the background of the user, familiarity may be gained by self-study or through training provided by the model provider.
- Training in application of the model: The model user must be made aware of the influential parameters which may affect the results of the inspection method and must understand the extent to which these are taken into account by the model. In particular, the model user must be made aware of the range of validity of the model with respect to the influential parameters.
- Updating knowledge: Since the modelling of inspection methods continues to evolve, model users should be given the opportunity to update their knowledge through such means as technical exchanges with model providers, study of the literature or participation in conferences.

7 References

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APPENDIX A: Issues to Consider when Using Models developed by other Organisations or when Extending the Scope of the Model Application

The authors of technical justifications will naturally turn first to models with which they are most familiar: models either developed within their own organisation or which have been procured but which have been in use for some time. The authors are likely to have a good appreciation of the strengths, weaknesses and regimes of validity of such models. Greater care is perhaps needed when considering the use of unfamiliar models. This applies whether the new model is to be bought in, or will be run on the authors' behalf by an external organisation. This Appendix provides guidance on some of the issues to raise with external organisations when considering the use or purchase of their models.

Purpose of the model: What is the main “output” of the model? What can the model be used for? Does the model include defects or is it mainly concerned with propagation?

Input and output details: What input information is required to run the model? What output information is generated? In what form is this output generated (e.g. tabular, graphical, field plots, etc)?

Units and coordinate systems: What is the primary unit of measurement utilised by the model? Can alternative units be used? What coordinate system does the model use? Is this coordinate system consistent with practical application?

Physical basis: What physical laws and equations is the model based on? What simplifying assumptions and approximations are made? Is the model mainly “geometrical” (e.g. ray tracing including refraction, reflection and mode conversion at boundaries) or does it include field theory for propagation and/or scattering at defects?

Regime of validity and level of accuracy: What materials can the model be used for (e.g. ferritic, homogeneous anisotropic, inhomogeneous anisotropic for ultrasonics)? What component geometries are allowed (e.g. flat plate, pipe, nozzle)? What defect types are allowed (e.g. planar, volumetric, rough, smooth, multiple, branched, embedded, surface-breaking etc, crack gapes, face contact)? What constraints are there on component or defect dimensions, defect orientation, probe type, etc? What assumptions are made about the sharpness of crack tips?

Status of model: Mature or still under development, extent of use on practical plant problems

System versus partial models: Is the model a full “system” model (modelling the full inspection process) or a “partial” model (modelling one specific aspect, e.g. the probe beam or the scattering by the defect)? If a partial model, how is the model output treated to relate to practical inspection problems?

Model dimensionality: How many spatial dimensions does the model have? (Two-dimensional models assume variation with two spatial co-ordinates only, with no variation in the third dimension. They are often used because they are simpler to formulate and require fewer computer resources than full three-dimensional models.) If 2D, how is the output related to 3D reality? Can “3D effects”, such as defect skew, be accommodated? Can effects due to the finite length of any defect in the third dimension be neglected?

Computer requirements: On which computer operation system is the model run on? Does it run under Windows, Unix or another operating system? What are the memory and storage requirements? Are other software packages required to run the model (e.g. CAD software or scientific routine libraries such as NAG)?

Typical run times: What are the typical computer run times for the model?

Extent of documentation: Is there a user manual or other documentation? Is there on-screen help? Are the underlying theories used in the model well-documented? If examples are provided, are they relevant to the application?

Ease of running: Does the model have a user-friendly interface? How is input data entered? How robust is the model in dealing with incorrectly entered data? Does the model provide error flags or warnings if it is used outside its regime of validity? How much training does a user require to run the model? Can the model be run by a general NDT engineer on an occasional basis, or should the model be run by specialists only?

Availability of support and training courses

Extent of validation against experiment: How thoroughly has the model been validated against experiment (or other theories)? Is this validation work well-documented? How relevant is the validation to the application?

Availability of model: Is the model available to buy? Is the owner willing to run the model on the customer's behalf?

Cost

Licence conditions: What conditions would apply to the customer's use of the model?

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Abstract

This document is ENIQ Recommended Practice 6 on the use of modelling in inspection qualification. Models have been developed by several organisations for various inspection situations and, where applicable, can provide valuable evidence on inspection capability for inclusion in a technical justification. Authors of technical justifications may therefore be considering the use of models, which may be available in-house, bought in from an external organisation, or run by an external organisation on their behalf. This Recommended Practice provides advice on:

- the types and range of available models;
- how the models can be used to generate evidence for a technical justification;
- important considerations and constraints in using models;
- validation of models;
- training on modelling.

ENIQ Recommended Practice 6 “The Use of Modelling in Inspection Qualification” was firstly issued in December 1999. It is a living document and reviewed regularly to account for the latest experience gained from the use of this recommended practice and the latest progress in modelling approaches and technology. This version is Issue no. 2.

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